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HIGH RESOLUTION STUDIES OF CALAVERAS FAULT SEISMICITY

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Technical Abstract

By measuring relative earthquake arrival times using waveform cross correlation and locating earthquakes using the double-difference technique, we are able to reduce hypocentral errors by 1 to 2 orders of magnitude over routine locations for nearly 8000 earthquakes along a 35-km section of the Calaveras Fault. This represents ~92% of all seismicity on this fault from 1984-1998 and includes the rupture zone of the M 6.2 1984 Morgan Hill, California, earthquake. The relocated seismicity forms highly organized structures that were previously obscured by location errors. There are abundant repeating earthquake sequences as well as linear clusters of earthquakes. Large voids in seismicity appear with dimensions of kilometers that have been aseismic over the 30-year time interval, suggesting that these portions of the fault are either locked or creeping. The area of greatest slip in the Morgan Hill main shock coincides with the most prominent of these voids, suggesting that this part of the fault may be locked between large earthquakes. We find that the Calaveras Fault at depth is extremely thin, with an average upper bound on fault zone width of 75 m. Given the location error, however, this width is not resolvably different from zero. The relocations reveal active secondary faults, which we use to solve for the stress field in the immediate vicinity of the Calaveras Fault. We find that the maximum compressive stress is at a high angle, only 13° from fault normal, even to within a few hundred meters of the Calaveras fault, supporting previous interpretations that this fault is weak.

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Non-Technical Abstract

By careful measurement of the arrival times of earthquake waves in combination with improved earthquake location techqniques, we are able to reduce earthquake location errors from over 1 km to 100 meters or less for nearly 8000 earthquakes along a 35-km section of the Calaveras Fault in California. The improved earthquake locations allow us to discern highly organized structures in the seismicity that were previously obscured. We find many sequences of repeating earthquake sequences, linear clusters of earthquakes, large voids in seismicity on the Calaveras fault. The relocations also reveal active secondary faults that support previous interpretations that the Calaveras fault is weak.

Introduction

The Calaveras Fault (figure 1) is one of the most active branches of the San Andreas system in northern California. In the 20th century there have been a series of moderate magnitude earthquakes some of which have repeated [Oppenheimer et al., 1990]. The largest of these earthquakes was the M 6.2 1984 Morgan Hill earthquake, which appears to have been a repeat of an earthquake in 1911. The long-term slip rate on the Calaveras Fault to the south of where the Hayward Fault splays from it is thought to be 15 ± 3 mm/yr [Working Group on California Earthquake Probabilities (WGCEP), 1999].

In addition to rupture in moderate earthquakes, this section of the Calaveras Fault has been extraordinarily active in microearthquake activity. It is also known to creep with an average rate of ~13.5 mm/yr since 1997 [WGCEP, 1999]. Because of the combination of a fast slip rate, the presence of creep, and equivocal paleoseismic evidence for large earthquakes in the past, the potential for future large earthquakes on the central section of the Calaveras Fault remains uncertain [WGCEP, 1999].

Oppenheimer et al. [1990] studied microearthquake activity of the Calaveras Fault in great detail. They found a correspondence between the areas that slipped in moderate earthquakes with areas that were relatively devoid of microearthquake activity. They also found that small earthquakes had a very similar spatial distribution both before and after moderate earthquakes. They proposed that the areas devoid of seismicity were stuck between moderate earthquakes and used this assumption to identify two likely source zones for future moderate earthquakes on the Calaveras Fault.

The geometry of fault zones within the Earth is revealed primarily by seismicity. In this study, we greatly improve the earthquake locations on the Calaveras Fault. Our ability to resolve fault zone structure and hence to address many essential aspects of earthquake behavior, is limited by our ability to obtain precise earthquake locations. While quantitative earthquake location techniques date back to the early years of the 20th century [e.g., Geiger, 1910], our incomplete knowledge of Earth structure and the difficulty of measuring arrival times accurately typically limits the accuracy of earthquake locations to tens of kilometers at teleseismic distances and several kilometers at regional distances even in well instrumented regions like California and Japan.

Uncertainty in earthquake locations can be dramatically reduced by aiming for precision, rather than accuracy, in the form of relative earthquake locations [e.g., Poupinet et al., 1984; Fre´chet, 1985; Deichmann and Garcia-Fernandez, 1992; Got et al., 1994]. In this study, we improve the precision of earthquake locations in two principal ways: (1) removing substantial velocity model error with the double difference approach [Waldhauser and Ellsworth, 2000] and (2) reducing relative arrival time measurement errors by waveform cross correlation [Schaff, 2001]. The combination allows us to reduce relative location errors by 1 to 2 orders of magnitude for the entire data set.

What emerges from the improved earthquake locations is a highly refined picture of seismicity on the Calaveras Fault (figures 2,3,4). Numerous features that were seen as clouds of seismicity are brought into sharp focus (figure 2). These features include streaks of earthquakes that are elongated in the direction of slip, repeating microearthquakes that recur up to dozens of times, and large areas of little seismicity. We obtain a clearer view of a kilometer-scale compressional fault offset and its geometry at depth. We are also able to resolve secondary fault structures, which were previously suggested by focal mechanisms [Oppenheimer et al., 1988]. Slip on these structures indicate that the maximum compressive stress is at a high angle to the Calaveras Fault implying that it is weak if the stress remains unfavorably oriented on the fault plane. This seems likely, as secondary structures are active to within 100 m of the main fault trace. If the stress rotates into a more favorable orientation, it must do so within several hundred meters of the fault. The improved locations also allow us to constrain the degree of strain localization on the Calaveras Fault. We find a very narrow fault zone width of no more than 75 m at seismogenic depths.

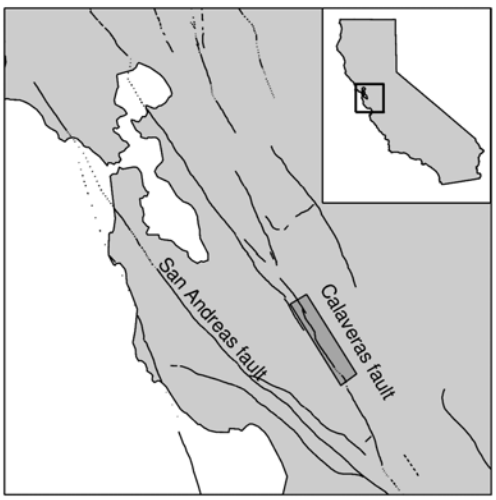

Figure 1. Study area is a 35 km segment of the Calaveras fault near San Jose, California. There were nearly 8000 earthquakes on the fault during the period of study. We used approximately 8,000,000 cross correlation arrival time measurements of *P* and *S* waves to relocate these earthquakes.

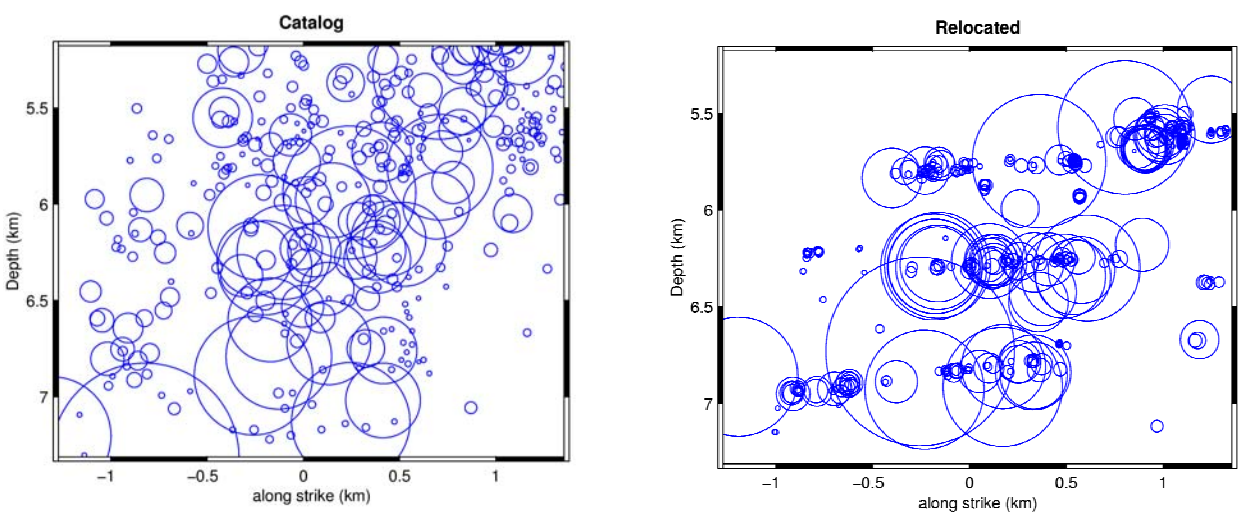

Figure 2. Improvement in earthquake locations is demonstrated by comparing the standard catalog locations (left panel) with the improved locations (right panel). The previously chaotic seismicity becomes highly organized after relocation.

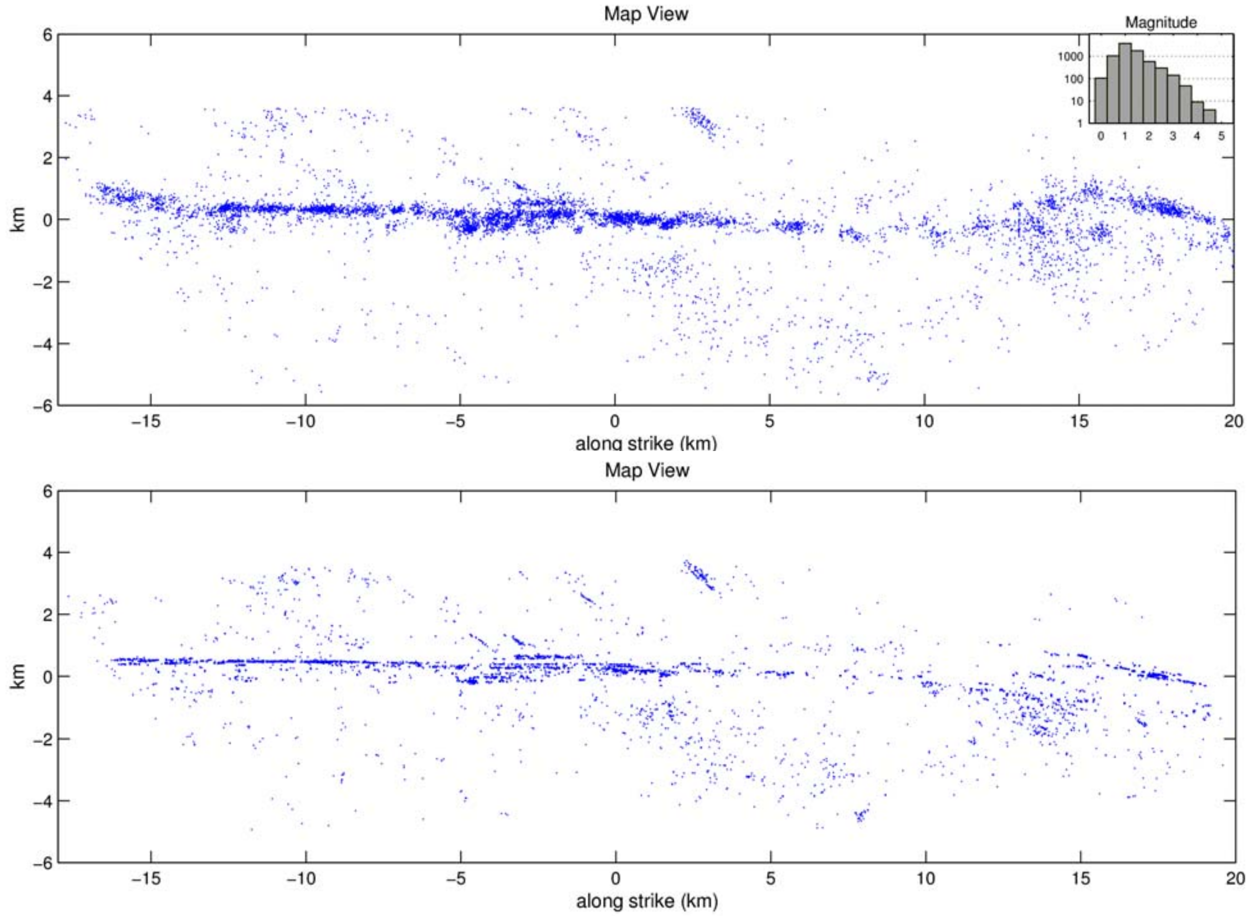

Figure 3. Map view of earthquakes before (top) and after (bottom) relocation. The map is oriented such that the trend of the nearly vertical Calaveras fault is horizontal on the figure. The fault discontinuity at 14-18 km along strike is much more clearly defined in the relocations. Many of the off-fault earthquakes above the fault in the figure show up much more clearly in the relocations. These are right-lateral (not conjugate) strike-slip faults and the trend of the microearthquakes is consistent with their focal mechanisms. The more diffuse seismicity shown below the mainshock fault plane defines a clear dipping planar fault in cross section. Here too the rreverse faulting focal mechanisms of these events is consistent with the planes of microearthquakes in the relocations. Together with the mainshock fault plane, these combinations of active faults constrain the maximum compressive stress to be nearly normal to the Calaveras Fault. The mainshock fault plane itself is much more sharply defined in the relocations and the width of the fault at depth is not resolvably different from zero.

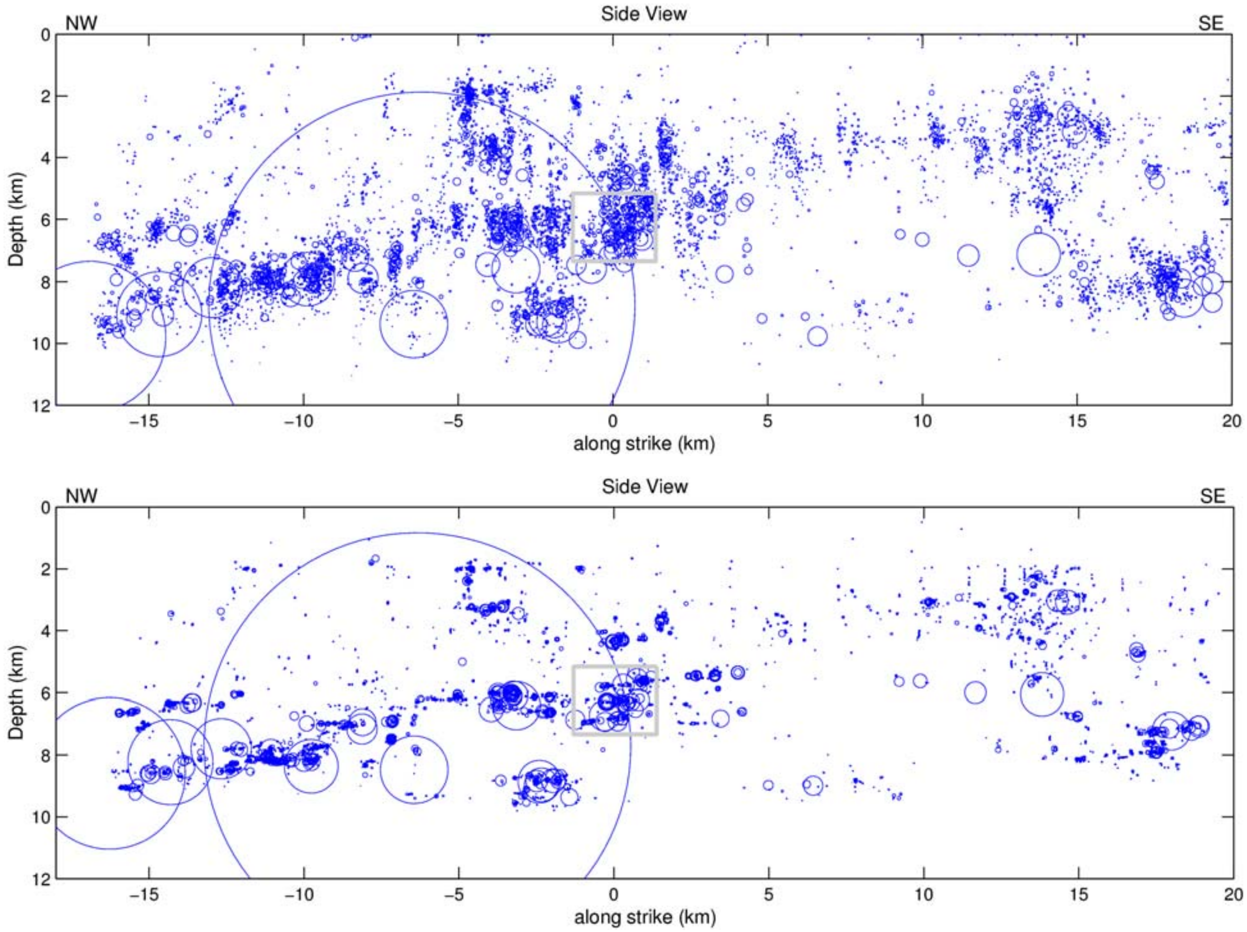

Figure 4. Side view of earthquakes before (top) and after (bottom) relocation. The earthquakes are plotted as circles with the size of the circle corresponding to that expected for a circular constant stress drop of 3 MPa. Much of the fault is not covered with seismicity and there are many areas of frequently repeating earthquakes. The large circle is the 1984 Morgan Hill California earthquake. This earthquake is large enough that there are independent determinations of the slip distribution from strong motion data [*Beroza and Spudich*, 1988]. These indicate that most of the slip occurred in areas devoid of microearthquake activity, which in turn suggests that these areas are locked between large earthquakes. The streaks of seismicity are roughly aligned with the slip direction. A temporary deepening of the deepest earthquakes from –1 to –4 km along strike (not shown) following the 1984 Morgan Hill earthquake is consistent with the notion that a strain-rate dependent rheology controls the depth of the seismic to aseismic transition.

A complete description of our results for the Calaveras Fault was published in the Journal of Geophysical Research as:

Schaff, D. P., G. H. R. Bokelmann, G. C. Beroza, F. Waldhauser, and W. L. Ellsworth, High resolution image of Calaveras Fault seismicity, *J. Geophys. Res*., **107** (B9), 2186, doi:10.1029/2001JB000633, 2002.

A description of the cross correlation measurement techniques that were used to develop these locations was published in the Bulletin of the Seismological Society of America as:

Schaff, D.P., G.H.R. Bokelmann, W. L. Ellsworth, E. Zanzerkia, F. Waldhauser, and G. C. Beroza, Optimizing correlation techniques for improved earthquake location, *Bull. Seismol. Soc. Am.*, **94**, 705-721, 2004.

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